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Integrating Cost Models with Systems Engineering Tools

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Integrating Cost Models with Systems Engineering Tools

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Abstract—**This paper considers cost modeling efforts within the Department of Defense over the last 30 years to formulate an approach for integrating cost modeling capability with the systems engineering tools developed under the Engineering of Complex Systems Block Program.**

I. INTRODUCTION

The need to build complex warfare systems within an industry characterized by the declining defense budget has increased the role of cost modeling for defense systems. Accordingly, systems engineering design synthesis methodologies must incorporate cost modeling capabilities to insure robust tradeoff analyses.

Ideally, a sound systems engineering design synthesis methodology assesses the tradeoff between development cost, long term life cycle cost (excluding development cost), time, and functional performance. Figure 1 portrays this tradeoff.

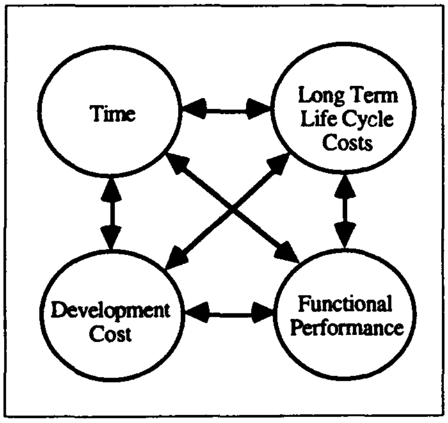

Fig. 1. Tradeoff analysis [1].

Realistically, the nature of projecting data for a warfare system platform that has a 30 year life cycle creates a significant variance on the data from any estimate. In the words of Paul G. Hough, one of RAND Corporation's premiere cost analysts: "cost analysis is subject to considerable uncertainty" [2].

The factors that contribute to the inexactness of cost estimates range from forecasting the cost/performance trends for new technology to projecting the rate of inflation for the life of the system. Short term estimates retain more accuracy than long term estimates; however, military systems require long term estimates. For these reasons, the tradeoff analysis often relies on qualitative data rather than quantitative data. The graph in figure 2 illustrates the difficulty historically encountered when forecasting the life cycle cost for complex military systems.

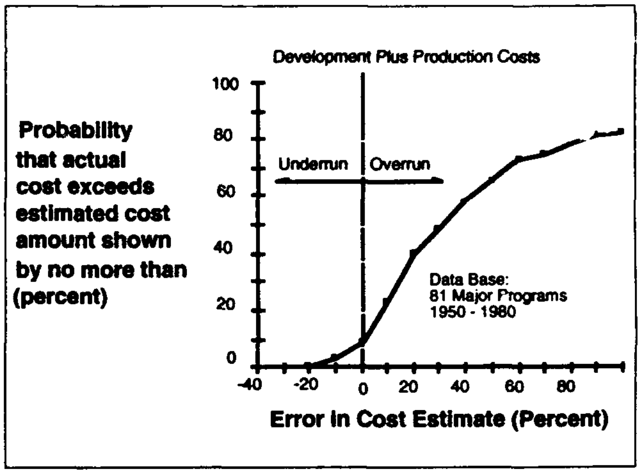

Fig. 2. Cost estimation track record [3].

This paper describes an approach for integrating cost modeling capability with the systems engineering tools developed by the Engineering of Complex Systems Block Program. The approach will:

- produce qualitative cost trends,
- incorporate detailed short term cost models,
- use heuristics for long term cost estimates, and

- incorporate existing models and tools, rather than develop new ones.

The goal is to enable systems engineers to perform qualitative cost tradeoffs while synthesizing complex engineering systems. Once the qualitative cost estimation capability has been incorporated into a systems engineering tool set, additional research can expand and refine the capability to provide more accurate cost estimation capability.

The discussion about the cost modeling integration approach advocated within this paper includes: a historical overview of cost modeling within the Department of Defense, a review of critical system design factors (SDFs) related to life cycle cost, an assessment of existing cost modeling tools, and a methodology for integrating cost models with the systems engineering tools developed under the Engineering of Complex Systems (ECS) Block Program. System Design Factors identify, and quantify important aspects of a system design [4]. The paper includes an extensive bibliography for the reader's benefit.

II. HISTORICAL OVERVIEW

From its inception as a specialized field in the early 1950's to the present time, military cost analysis has evolved into an integral component of the decision making process for military system development. As cost analysis evolved, new methodologies were developed to improve the estimates.

In the 1950's cost analysis primarily evaluated cost estimates provided by contractors. Analysts compared the estimates against the cost of similar systems. This estimation methodology became known as "analogy" and will be described later in this section.

The 1960's was characterized by centralized decision making brought about by Secretary of Defense Robert McNamara and his "whiz kids". Cost analysis became an important aspect of the budgeting process as the nation struggled with funding the Vietnam War effort without adversely affecting the economy [2].

In the 1970's cost became a parameter of equal importance to performance. DoD Directive 5000.1 instituted the Design to Cost (DTC) concept. DTC led to the development of parametric model cost estimating. Life cycle costing (LCC) emerged when it became apparent that the existing models were deficient in estimating Operating and Maintenance (O&M) costs [2].

In the 1980's the Reagan administration instituted the Carlucci initiatives. The initiatives set out to improve the military procurement process. The legacy of the 1980's increased the media and public focus on cost analysis due to congressional hearings, legislation and high profile weapons systems.

Currently in the 1990's DoD has focused on developing affordable military systems. Cost has become a driving parameter. As a result the accuracy of cost estimates is critical; however, current state-of-the-art cost analysis does not, in most cases, provide better than a rough order of magnitude estimates [7]. Consequently, tradeoff analyses often rely on qualitative rather than quantitative estimates.

The importance of LCC, identified in the 70's, is reflected in the concept of viewing the life cycle and the associated costs in three distinct phases. These phases are research and development (R&D), investment (including production) and operation and maintenance (O&M).

R&D cost refers to all costs associated with research, development, test and evaluation of the system. This covers all costs during the validation and full scale development phase of a program. The costs associated with this phase end with the satisfactory completion of the initial operational test and government approval for use.

Investment cost refers to all costs associated with the production of the system. The costs incurred during this phase are complete when the operational system is delivered to the procuring command for use.

O&M cost refers to all cost associated with the operation and logistics support of the system subsequent to the delivery of the system.

DoD cost analysts focus on these three phases of the life cycle and their contribution to the overall life cycle cost. Cost related system design factors identify the components associated with each phase in greater detail.

III. SYSTEM DESIGN FACTORS

System Design Factors provide a mechanism to quantify system characteristics for tradeoff analyses [4]. Tables I-III contain the SDFs for cost and their assignment to the three phases of the life cycle.

When considering SDFs related to cost, a systems engineer should concentrate on the most critical SDFs for each stage of the life cycle. Focusing on the SDFs that provide the most significant contribution to the cost at each stage of the life cycle, reduces the number of factors required for a total rough order of magnitude cost estimate.

For R&D cost the significant SDFs are: engineering, software, documentation, and test and evaluation. Engineering includes costs related to systems engineering and integration, design engineering, design support, and the redesign or formulation of engineering changes [5].

TABLE I
R&D SYSTEM DESIGN FACTORS [5]

R&D		
Validation	Engineering	[illegible]e
Program Management	Prototype Hardware	[illegible] & Test Equipment
Documentation	Test Spares	Test Facilities
Test Personnel Training	Test & Evaluation	

TABLE II
INVESTMENT SYSTEM DESIGN FACTORS [5]

Investment		
Production Hardware	Program Management	Training
Integration & Test	Production Test and Evaluation	Documentation
Production Support & Services	Industrial Facilities	Initial Spares
Installation and Checkout	Support & Test Equipment	Transportation
Operational Sites	Maintenance Sites	Supply Introduction

TABLE III
O&M SYSTEM DESIGN FACTORS [5]

O&M		
Crew	Facilities	Material
Personnel	Modernization	Overhaul
Software Maintenance	Preventative Maintenance	Corrective Maintenance
Operator Training	Support and Test Equipment Maintenance	Replenishment Spares
Inventory Storage	Supply System Management	Repair Material
Documentation Maintenance	Shop Space	Shipping
Packaging Material	Material Handling Labor	

For Investment cost (includes production) the significant SDFs are: production hardware, production support and services, initial spares, operational sites, and maintenance sites.

For Operating and Maintenance cost the significant SDFs are: crew, material, preventative maintenance, corrective maintenance, and modernization.

The aforementioned cost related system design factors become the focus of cost estimation efforts for a warfare system. Analysts have developed several techniques to estimate the components of life cycle cost for military systems.

IV. COST MODEL ASSESSMENT

Presently DoD cost analysts use four basic cost estimation methods [6]. These methods are: analogy, expert judgment, bottom up (Industrial Engineering), and top down or parametric estimation. Table IV presents a comparison of the four methods.

TABLE IV
METHODOLOGY COMPARISON

Method	**Accuracy**	**Time**	**Historical Dependence**
Analogy	Low	Medium	High
Expert Judgment	Low	Low	High
Bottom Up	Medium	High	Medium
Top Down	Medium	Low	Low

Analogy involves the comparison of similar systems. The analyst compares attributes of similar systems to determine a reasonable cost estimate. This approach requires a fair amount of experience, as well as historical data. The estimate is highly subjective to the bias and experience of the analyst. The method assumes the use of similar technologies. Nevertheless, the estimate can be generated quickly.

Expert Judgment is similar to analogy because the estimate can be generated quickly. In this approach, an "expert" uses his experience to generate a cost estimate. As with analogy, the estimate is sensitive to inaccuracies due to the subjective nature of the expert's opinion. This method depends highly on the availability and skill of experts.

The Bottom Up or Industrial Engineering method represents a more objective approach. This method divides the estimation task into smaller units. An individual or group who has the appropriate data, experience and model to generate an accurate result produces the estimate. The sum of the unit costs determines the total cost. This approach yields a more

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accurate estimate, but it is time consuming. The availability of unit cost data determines the accuracy of the Bottom Up approach.

Top Down or Parametric Estimation is the most widely used cost estimation method within DoD [6]. This method relies on computer models to obtain the cost estimate. The analyst provides lower level design parameters as input to the model. Generally these models are easy to use, and produce a more accurate result. The difficulty with using parametric models is that occasionally the required input parameters may not be known or may be difficult to quantify. The lower level nature of some of the parameters often means they are difficult to define until the design progresses.

DoD uses parametric models primarily to estimate software costs. One reason for this is that software cost is a significant component of the system life cycle cost. In addition it appears that software cost may be more difficult to determine using the other estimation methodologies.

A variety of software cost estimation models exist. Many are proprietary. The more widely used models include [6]:

- Constructive Cost Model (COCOMO),
- PRICE-S,
- System Evaluation and Estimation of Resources (SEER),
- Software Life Cycle Cost Model (SLIM),
- Revised Enhanced Version of Intermediate COCOMO (REVIC), and
- Software Architecture, Sizing and Estimating Tool (SASET).

The models require the user to provide specific parameters that quantify and describe their system. The parameters required by the models cover: lines of code, language, number of programmers, experience of programmers, development platform, availability of tools, reliability and schedule. Analysts may have difficulty quantifying some parameters requested, such as developer experience. However, these models provide an estimate rather quickly. In addition, the models are generic, that is the software models can be applied to estimate costs for any application. System engineers using these models should understand that these models often are difficult to calibrate [7], and require recalibration for different environments [8].

While many generic models exist for software cost estimation, the same is not true for other aspects of the life cycle cost. These costs are generally computed by analogy, expert opinion or by models developed for a specific application. The models use heuristic data bases from existing combat systems to estimate cost. For example at the Naval Undersea Warfare Center (NUWC), several combat system specific cost estimation models exist based on data from existing submarine warfare systems.

The current state-of-the-art in cost estimation technology relies on generic models to estimate software costs and expert judgment/heuristic models for other components of the life cycle cost. Therefore, the integration of cost models with systems engineering tools should be flexible to incorporate the different types of models available for each phase of the life cycle.

V. Integrating Cost Models

The integration of cost modeling capability into systems engineering tools will enable systems engineers to perform qualitative cost tradeoffs while synthesizing complex engineering systems. The objectives of the cost model integration process encompass:

- defining cost related systems design factors,
- pinpointing critical cost related system design factors,
- providing systems engineers with qualitative cost factors for systems design synthesis,
- linking cost related system design factors to the Design Structuring and Allocation Optimization (DESTINATION) systems engineering tool, and
- permitting design factor optimization within DESTINATION.

Existing cost models will be used in order to expedite the availability of cost modeling capability. Figure 3 depicts the method which will integrate cost models with the DESTINATION systems engineering tool developed by the Engineering of Complex Systems Program.

The method breaks down the cost models into three different categories: hardware research and development, software research and development, and the remaining life cycle costs. The hardware and software research and development cost models are kept separate because detailed cost databases exist for hardware, and established models exist for software (refer to the *Cost Model Assessment* section of this paper for examples of existing databases and models). Heuristics will provide information for the remaining part of a system's life cycle. Heuristics are readily available and produce satisfactory information for this stage of the cost model integration process.

The link to DESTINATION will occur through the Systems Engineering Technology Interface Specification (SETIS) software. SETIS interface software will be developed to provide a link to the cost models. The SETIS link ensures compatibility with other tools developed within the Engineering of Complex Systems Program. System design factors describing the hardware resources, software design, functional requirements and programmatic requirements will be extracted from DESTINATION through SETIS. Additional, lower level, SDFs will be defined during the model integration process. The cost model will supply information regarding cost related system design factors to DESTINATION through SETIS.

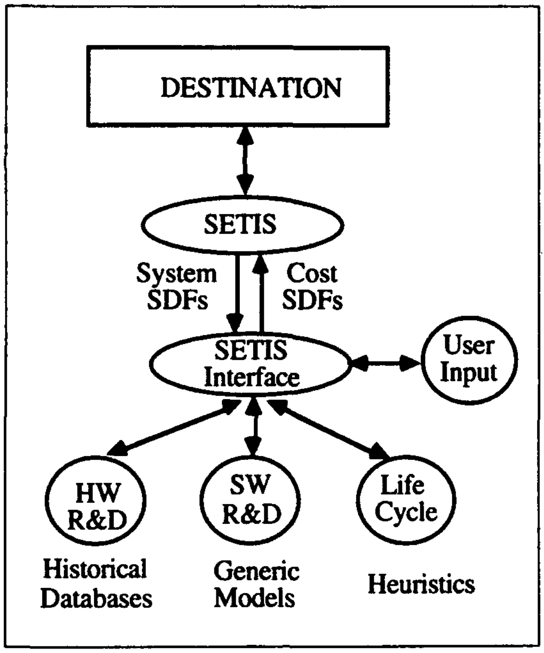

Fig. 3. Integration with DESTINATION.

If the system specific information currently provided by DESTINATION is inadequate, then the user must provide additional information to the cost models. The SETIS interface will also query the user to input the additional information and incorporate the data into the cost estimate.

The SETIS interface will manage the data generated from the hardware R&D, software R&D, and life cycle cost models. The interface software will require the development of C++ code to maintain compatibility with SETIS. SETIS was implemented using a C++ class hierarchy [9]. The intent is to develop cost modeling capability that requires minimum modification to existing SETIS software.

The cost related system design factors described in this paper will serve as the foundation for the cost models. The system design factors listed in *NAVSWC Technical Report 92-268* will also receive consideration. These system design factors include cost to: develop, prototype, produce, test, purchase, operate, maintain, repair, include security capability, and achieve productivity.

Once the concept has been demonstrated, the repertoire of cost models can be expanded to give the systems engineer different options and perspectives. Each new model would be linked to DESTINATION through SETIS, and the SETIS interface software developed for the cost models.

In addition to the integration of cost modeling capability with DESTINATION, the approach outlined can also be applied to the integration of commercially available system engineering tools. By using the CASE Document Interchange Format (CDIF) instead of SETIS, the cost estimation models can be integrated with system engineering tools such as RDD-100, Cadre Teamwork and others. Of course this approach assumes that these tools comply to the standardization of CDIF. If the selected tools don't comply with CDIF, some translation between specific formats may be required to interchange data between tools.

VI. SUMMARY

This paper describes an approach for integrating cost modeling capability with the systems engineering tools developed by the Engineering of Complex Systems Block Program. The approach entails:

- using existing hardware R&D cost databases,
- incorporating established software cost models,
- estimating long term life cycle cost with heuristics,
- defining cost related system design factors, and
- designing a software interface to DESTINATION via SETIS.

The cost modeling integration approach was conceived by tracing through the history of cost modeling within the Department of Defense, defining cost related system design factors, assessing existing cost modeling tools, and formulating a methodology for integrating cost models with the systems engineering tools developed under the Engineering of Complex Systems Block Program.

A qualitative cost estimation capability will enable system engineers to perform tradeoffs while synthesizing complex engineering systems. The fundamental tradeoff between development cost, long term life cycle cost, time and performance is the primary objective.

Finally, the cost modeling research that led to the proposed cost modeling approach produced an extensive list of references. Although many of these references were not explicitly used within the context of this paper, the full list is included for the reader's benefit.

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